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**MECHANICAL DESIGN OF  
SERT II THRUSTER SYSTEM**

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16. Abstract  This report describes the mechanical design of the mercury bombardment thruster that was tested on SERT II. The report shows how the structural, thermal, electrical, material compatibility, and neutral mercury coating considerations affected the design and integration of the subsystems and components. The SERT II spacecraft with two thrusters was launched on February 3, 1970. One thruster operated for 3782 hours and the other for 2011 hours. A high voltage short resulting from buildup of loose eroded material was believed to be the cause of failure.					
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# MECHANICAL DESIGN OF SERT II THRUSTER SYSTEM

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## SUMMARY

The SERT II (Space Electric Rocket Test) spacecraft had two mercury bombardment thrusters. The primary objective of the flight was to endurance test the thruster system. The thrusters were operated one at a time. The thrust from one thruster raised the spacecraft orbit while the thrust from the second thruster lowered the orbit. A 6-month thrust interval from one thruster would have caused a change in orbit height of approximately 120 kilometers.

This report describes the mechanical design of the SERT II mercury bombardment thruster. It shows how the structural, thermal, electrical, material compatibility, and neutral mercury coating considerations affected the design and integration of the subsystems and components. The vibration and shock testing is covered.

The thrusters passed all preflight testing. The standby thruster was run in space for only 2 days to confirm operation. The primary thruster was then run for a total of 3782 hours with two brief interruptions. The stand by thruster was restarted and run for 2011 hours with one interruption. The cause of the failures was believed to be ion sputtering between the screen grid and accelerator plate which resulted in undercutting and wear on the molybdenum plates. The loose molybdenum particles formed a conductive path between the grids which resulted in a high voltage short.

## INTRODUCTION

The primary objective of the SERT II (Space Electric Rocket Test) flight (launched Feb. 2, 1970) was to provide a 6-month endurance test of a flight-type mercury bombardment thruster. The secondary objectives consist of validation of ground test results, determination of the ion thruster operating characteristics in a space environment, development of operational procedures for an ion thruster system and the determination of the reliability endurance capability and the compatibility of an integrated thruster system.

The SERT II assembly was launched by a Thorad-Agena booster into a 1000-kilometer circular orbit (see fig. 1). The second stage Agena, spacecraft support unit and spacecraft make up the SERT II assembly (see fig. 2). The spacecraft had two complete thruster systems. Only one thruster was operated at a time with the other system held in "standby." The thrust from one unit resulted in orbit raising while the thrust from the second unit lowered the orbit. A 6-month thrust interval from one thruster will cause a change in orbit height of approximately 120 kilometers.

Previous to this launch, a mercury bombardment thruster (SERT I) was launched in June 1964 into a ballistic trajectory to demonstrate that an ion thruster could be operated and the beam could be neutralized in space. The SERT I thruster is shown in figure 3. The results of this flight are discussed in reference 1.

This report describes the mechanical and structural design of the SERT II thruster system. The subsystems and components are described in enough detail to show how the design was affected by the structural, thermal, electrical, material compatibility, and neutral mercury coating considerations. The arrangement and fabrication techniques are described to show how the functional requirements were met. The environmental testing described is limited to vibration and shock. The thruster operation and performance is explained in references 2 and 3.

## THRUSTER SPECIFICATIONS

The thruster specifications had been determined by previous research and project requirements. The final design specifications are listed in table I. The 1000-watt thruster selection was based on the limitations of the launch capabilities of the Thorad-Agena vehicle and the available solar array supply. The 14-kilogram propellant mass was based on a 6-month duration plus contingencies for a possible 9 months supply. The other magnitudes were based on the best state of the art in ion thrusters. The dynamic characteristics of the Thorad-Agena booster required that the thruster hardware be designed to pass the dynamic environmental specifications listed in table II.

## THRUSTER SYSTEM DESIGN

### General Description

Two thruster systems are located on opposite sides of the 1.5-meter-diameter spacecraft (see fig. 2). The thrusters are tilted  $10^{\circ}$  away from the centerline of the spacecraft. Each thruster is mounted on a gimbal system that is capable of orienting the thruster in two planes ( $\pm 10^{\circ}$ ). The thruster system arrangement is illustrated in

figures 4 and 5. Basically, liquid mercury is stored and pressurized in the feed tanks, vaporized and controlled in the cathode assembly, then ionized by electron bombardment of the mercury vapor molecules in the discharge chamber. The trajectory inside the discharge chamber is partially controlled by a divergent magnetic field provided by the bar magnets and the pole pieces. These ions are accelerated and directed by the high voltage between the screen and accelerator grid plates. The ion beam is neutralized by the neutralizer cathode assembly. Each thruster is designed to supply 2.81 grams of thrust with a specific impulse of 4460 seconds.

Sheet metal construction was selected in most cases to provide the lightest weight. The manufacturing and assembly processes were controlled carefully to give the desired results. After forming or machining and welding, the hardware was penetrant inspected to discover any flaws or cracks. The hardware was ultrasonically cleaned, surface treated where necessary, recleaned, assembled, and packaged in a clean atmosphere. The components and subassemblies were joined by electron beam and tungsten inert gas welding where practical. Self-clinching nut plates, lock nuts, and socket head cap screws were used as fasteners. Where lock-type nuts were not practical, lock wire was used to give a reliable joint.

Since it was required to gimbal the thruster in two directions, a rigid structure was designed to be compatible with a gimbal ring and serve as a reliable structural tie for the thruster system (see figs. 4 and 5).

The thruster system is composed of a discharge chamber assembly, main cathode assembly, neutralizer system, feed tanks, thruster-gimbal support, electrical wiring, and ground screens. This thruster system including the loaded feed tanks weighed 25.8 kilograms. The subassemblies, systems, components, and dynamic testing are described.

## Discharge Chamber Assembly

The main design goal of the discharge chamber was the selection of materials, fastening techniques, arrangements, and isolation methods that gave the lightest structure and also permitted the discharge chamber to perform its intended function without any failures due to environmental conditions. Many of the parameters such as the discharge chamber volume, anode size, thruster potential, the number of magnets, the size and number of screen holes, and in most cases the spacing were predetermined. The discharge chamber was located and isolated on four pedestals (see fig. 6) elevated 6.7 centimeters above the thruster support. These pedestals also provided a compact arrangement for integrating the feed tanks and cathode assembly to the thruster support structure.

Discharge chamber. - The discharge chamber (17.6 cm diameter by 12.6 cm long by 0.038 cm wall thickness) served as the structural mount for the discharge chamber components (see figs. 6 and 7). The anode is mounted inside the discharge chamber. The distributor enclosure pole piece and cathode assembly are mounted at the lower end of the chamber. The screen and accelerator grids, neutralizer, and ground screen attachments are located at the top. The 304 stainless-steel cylinder is rolled with three identical circular beads (0.15 cm radius) located along the surface to provide the structural stiffness required to carry the radial loads and give the desired resonant frequency. The chamber is seam welded along the one side with tungsten inert gas arc welding. The top of the discharge chamber is also stiffened by a collar of the pole piece that is riveted to the discharge chamber.

Anode. - The 304 stainless-steel anode (15.2 cm diameter by 10.2 cm long by 0.038 cm thick) was rolled and welded similar to that of the discharge chamber with the exception that the three beads (0.15 cm radius) were raised (see fig. 4). The anode is mounted inside the discharge chamber separated by six aluminum oxide insulators (see figs. 6 and 7). The insulators are composed of a male and female part with the separation occurring at the discharge chamber. Shadow shielding is used to form a gap between the anode and discharge chamber. Thin washers are added to complete the shadow shielding.

Magnets and pole pieces. - Eight Alnico V bar magnets (0.63 cm diameter by 12.0 cm long) are equally spaced around the arc chamber. These are held in place by sockets in two pole pieces (see figs. 6 and 8). The tolerances are set such that the mean dimension from the bottom of the socket on the upstream pole piece to the bottom of the socket on the downstream (top) pole piece is slightly smaller than the length of the magnets. This stack up of tolerances provides for continuous contact between the magnets and pole pieces. In addition to preventing a possible loss of field strength these tolerances prevented a magnet from banging during environmental testing. The magnets are reversed on the two thrusters located on the spacecraft. On one thruster the north pole is located at the downstream pole piece and on the other thruster the north pole is at the upstream pole piece. This is done to balance the magnetic moment of the spacecraft and reduce residual torques. The pole pieces are machined from low carbon steel (SAE 1010-1030) to provide the required magnetic field. Nut plates are riveted to the downstream pole piece for mounting the screen grid.

The upstream pole piece (bottom) is designed as a part of the distributor enclosure and cathode assembly. The carbon steel parts were nickel plated per AMS 2405 (0.0025 cm thick) to prevent oxidization.

Screen and accelerator grids. - The screen and accelerator grids are flat plates of annealed molybdenum located in assembly 0.25 centimeter apart (see figs. 6 and 9). An array of 847 holes were drilled in the separate plates within a 14-centimeter-diameter pattern. The 0.40-centimeter-diameter holes in the 0.076-centimeter-thick screen grid

provides a 72 percent open area. The 0.33-centimeter-diameter holes in the 0.15-centimeter-thick accelerator grid provides an open area of 50 percent.

The hole pattern in these two grids are alined within 0.00254 centimeter. This accuracy was maintained by machining the holes on a numerical control drill press and by closely monitoring the tool wear. Since the hole pattern of the screen and accelerator is identical, the same tape was used. It was only necessary to change the drill size for obtaining the correct diameter of hole. The mounting holes were also machined on the same numerical control machine. The grid plates are annealed after machining. Three grid plates are clamped between two rigid flat plates and placed in an oxygen free atmosphere furnace. These are held at 1394 K for 15 minutes and furnace cooled. This operation eliminated any residual stress in the plates due to machining and minimized warping and shifting during thruster operation.

The screen grid is mounted to the downstream pole piece. Isolation shields and spacers are riveted to the screen grid. This attachment put the screen grid, arc chamber, pole pieces, distributor enclosure, and cathode assembly at the same potential (see fig. 9). This is the high voltage section of the thruster. The accelerator grid plate is mounted to the screen grid by an isolation system that was used on SERT I (see fig. 10). The same isolation system is used to mount the thruster on the four pedestals. This mounting technique provides a good electrical isolator, a good thermal isolator, and a rigid self-alining mechanical mount. Four equally spaced mounts using single crystal synthetic ruby balls (1.27 cm diameter) separated the screen and accelerator grids. Each ball is shadow shielded by overlapping cups to prevent mercury or sputtered materials from coating the balls and thus causing loss of isolation. A small slot is machined in the center member where the two balls mount in order to outgas the volume entrapped by the balls.

## Main Cathode Assembly

The main cathode assembly vaporizes the mercury, controls the flow and distribution of the propellant, and emits electrons into the discharge chamber. The thermal requirement of this assembly made it necessary to numerate and follow carefully the assembly sequences. The assembly sequences and the final geometry were determined analytically and experimentally to provide adequate thermal gradients. The assembly consisted of a hollow cathode, the thruster vaporizer, the isolator, keeper, cathode mount, and distributor enclosure (see figs. 9 and 11).

Hollow cathode. - About 10 percent of the propellant flow is directed through the hollow cathode. The remainder of the flow is through the distributor enclosure. The nominal operating temperature of the hollow cathode (1344 K) required that the selection of materials, assembly techniques, and welding processes be carefully controlled (see

fig. 12). The center portion of the cathode was made from a 0.32-centimeter-diameter tantalum tube with 0.038-centimeter-thick wall. The tube was counterbored at the end for accepting a 0.1-centimeter-thick disk (cathode tip). The 2 percent thoriated tungsten disk was electron beam welded to the tantalum tube. The cathode tip hole (0.02-cm diameter inside, 0.03 cm diameter outside) in the disk was started by blasting (using a 0.018-cm-diameter nozzle) with aluminum oxide grit until the abrasive material just started through. A carbide drill was used to complete the hole. A coating (0.0025 cm maximum thickness by 2.0 cm long) of powdered tungsten (plasma alloy 117M) was sprayed on the tantalum tube. This tungsten layer provided a barrier between the tantalum and aluminum oxide coating (added later) to prevent a material reaction at high temperature. A layer (0.0025 cm maximum thickness by 1.27 cm long) of aluminum oxide ( $\text{Al}_2\text{O}_3$ ) was sprayed over the tungsten. These two layers are sprayed on the tube before an insert is put in the tube to prevent the heat of additional flame spraying from destroying the chemical coating of the insert. The insert is placed inside the tantalum tube adjacent to the cathode tip to provide a small amount of thermionic electron emission. In addition, it serves as a reservoir of active oxide material to ensure restart capabilities. The insert is made from a 0.001-centimeter-thick tantalum foil coated with 0.002-centimeter-thick layer of barium carbonate (R - 500) and cut to produce a hollow cavity before it is rolled and inserted. This insert is held in position and at the same potential as the cathode by welding the insert to a tantalum wire and then electron beam welding the wire to the center tube. The cathode is heated by a coil of tungsten-26 percent rhenium wire that is insulated by various layers of aluminum oxide spray and radiation shielded by layers of 0.0012-centimeter-thick tantalum foil (see fig. 12).

The heater wire lead (coaxial) design is the same as that described under the main vaporizer. A tantalum heater lead (0.05 cm diameter) was used up to the cathode heater coil to keep the resistance of the connection low. The junction between the heater and lead wire was made by crimping a tantalum tube (0.15 cm by 0.46 cm by 0.02 cm wall thickness) over the mating part (see fig. 12, section A-A). To form a mating surface with the cathode mount, a larger tantalum tube (0.67 cm diameter by 0.94 cm long by 0.2 cm thick) was assembled over the end of the hollow cathode.

• Thruster vaporizer. - The vaporizer acts as a control valve for the propellant flow (see figs. 13 and 14). In this interface liquid mercury is held against a porous plug by the pressure in the feed tank. The plug density prevents liquid mercury from leaking through due to feed tank pressure and the added pressure due to dynamic loads. The mercury is vaporized by a heater coil that is wrapped around a tantalum enclosure. The porous plug permitted the mercury vapor to flow. The amount of vapor flow is dependent upon the amount of power added to the heater coil.

The porous tungsten plug (0.58 cm diameter by 0.15 cm thick) is 0.75 to 0.79 percent dense. It is made in sheet form from sintered spherical tungsten powder. The plug is electrical discharge machined from the sheet. The plug edge is turned

in a lathe to size the diameter and then electron beam washed on the edge to close the pores. The porous plug is electron beam welded into the vaporizer enclosure. The vaporizer enclosure is machined from tantalum and electron beam welded together. The stainless steel elbow tube from the isolator and the tantalum tube from the feed tank were electron beam welded to the vaporizer enclosure. The tantalum flange that mounts to the feed tank is electron beamed welded to the other end of the tantalum tube.

The vaporizer heater supplies sufficient heat to the vaporizer enclosure to permit the porous plug to operate at approximately 573 K (see fig. 13). The Nichrome V heater wire (0.05 cm diameter) is insulated by unfired aluminum oxide and enclosed by a sheath of tantalum tubing (0.2 cm diameter by 0.023 cm wall thickness). The coaxial design is assembled and swagged from a 0.20 centimeter diameter down to 0.15 centimeter diameter. This operation crushes the aluminum oxide and compacts the system to remove voids and trapped air. A commercial hermetic seal (Alite) was modified to isolate the outside sheath from the junction to the center conductor. This isolation technique reduced the resistance in the lead to the heater and isolated the high potential of the vaporizer enclosure from the heater input source. The hermetic seal also gave a longer path which made it more effective as an isolator.

Holes were drilled through the metal isolator cover to outgas the cavity that is formed when the seal is mounted to the heater wire. The fabrication and assembly of the heater lead to the hermetic seal is illustrated in figure 15. The outside sheath is cut back. A nickel tube was put over the heater wire to conduct current and keep the high resistance length as short and effective as possible. A 0.15-centimeter gap is left from the end of the nickel to the outer sheath of the heater for isolation. A 0.32 centimeter outside diameter stainless tube is put over the outside sheath of the heater and a spacer is used to step the tube up to the outside stainless sheath of the hermetic seal. Aluminum oxide is used to separate the stainless-steel tube and the center conductor. The heater wire is extended beyond the end of the center conductor of the hermetic seal and the nickel. The heater is slipped on the vaporizer and the complete assembly is furnace brazed with 88 percent copper, 12 percent nickel brazing alloy. The end of the heater wire is grounded to the vaporizer body during the brazing operation. The end of the center conductor is cut off flush with the end of the center conductor of the hermetic seal.

Dummy isolator. - The purpose of an isolator is to electrically isolate the high voltage section of the thruster. Since the development of an isolator was too late for the launch, a 304 stainless-steel dummy was fabricated and furnace brazed to fit the same configuration as the isolator. The dummy was heated by a heater coil similar to that described for the vaporizer. The bent tube (0.32-cm-diameter by 0.058-cm-thick wall) connecting the dummy isolator to the vaporizer was made of 304 stainless steel. This material was compatible with the dummy isolator material and took advantage of the larger sectional modulus of the tantalum vaporizer junction. The reason for a

larger sectional modulus is described under thruster tests. The tube was fastened at each of the junctions by electron beam welding.

Cathode baffle. - The baffle helps control the coupling voltage of the hollow cathode to the anode. The tantalum baffle (2.54 cm diameter by 0.025 cm thick) with six (0.47 cm diameter) equally spaced holes is supported by three 0.16-centimeter-diameter tantalum wires (see fig. 16). The wires are attached to a tantalum ring (3.8 cm diameter by 1.12 cm wide by 0.05 cm thick). These three parts are electron beam welded together and then riveted to the upstream pole piece.

Cathode mount. - The vitrified alumina (96 percent  $\text{Al}_2\text{O}_3$ ) mount serves as a locator and a rigid support for the hollow cathode as well as a means of reducing propellant leakage. In addition, it prevents discharge from taking place in the cathode cavity (see fig. 16).

Keeper. - The keeper produced a high electric field gradient for starting. It is located close to the cathode. It is formed and electron beam welded in the shape of a toroid (1.7 cm outside diameter) from a 0.15-centimeter tantalum wire (see fig. 16).

Distribution enclosure. - The distribution enclosure accepts the propellant and distributes it to the discharge chamber (see fig. 17). The enclosure was made from cold rolled bar and sheet (SAE 1010-1030) to be compatible with the top pole piece material and provide the magnetic path. The surfaces were nickel plated (AMS 2405 (0.0025 cm thick)) to prevent oxidization. The machined cylinder (cathode cavity) is brazed to the distributor bonnet. The bonnet and cavity are brazed (per MIL-B-9972 using AMS 4779 brazing alloy) to the upstream pole piece. The cathode cavity and the pole piece each have equally spaced holes (0.98 cm diameter) that provides for the flow of the propellant. These holes are covered with 40 mesh 304 stainless wire (0.005 cm diameter by 1.27 cm wire) resistance welded around the holes. This wire mesh is required to prevent discharge from taking place in the enclosure.

## Neutralizer Assembly

The neutralizer assembly provided the necessary electrons to neutralize the beam (see figs. 18 and 19). The assembly is electrically isolated from the remainder of the thruster system. A single isolation mount of vitrified alumina (96 percent  $\text{Al}_2\text{O}_3$ ) is used to separate the top of the neutralizer from the screen grid. The isolation mount is fastened to the lower portion of the ground screen ball mount. This location permits clamping the neutralizer tube just in front of the vaporizer. This point was selected as a compromise to prevent a cold spot between the vaporizer and cathode and to reduce the natural frequency of the cathode under vibrational loading. The major components of the neutralizer assembly consist of a cathode, vaporizer, keeper, and feed tubes.

Cathode. - The cathode is tipped about  $19^{\circ}$  from the plane of the accelerator plate out of the main thruster ion beam (approximately 2 cm radially and 2 cm outward from the accelerator grid opening). This location is sufficient to avoid direct impingement of the high velocity ion beam and provide optimum potential (coupling voltage) between cathode and ion beam. The materials, geometry, and assembly sequences of the neutralizer cathode are the same as that described for the thruster cathode except the 0.64-centimeter-diameter tantalum tube for fitting into the aluminum oxide baffles was not required.

Vaporizer. - The vaporizer and heater materials and assembly sequences are similar to that of the main cathode vaporizer and heater. The vaporizer plug is one-half the size of the main cathode vaporizer (0.32 cm diameter against the 0.64 cm diameter). The vaporizer enclosure was formed by counter boring one tantalum tube and swaging the adjoining tantalum tube to flare over the counter bored tube. The porous plug and the plug enclosure were joined by electron beam welding. The vaporizer heater was positioned close to the enclosure and brazed to the tantalum tube. This heater provided sufficient heat for the plug to operate at about 572 K. Since the cathode heater is also grounded to the tantalum tube, the cathode heater and vaporizer heater are in series.

Keeper. - A keeper is required to draw a sufficient discharge current to sustain a plasma bridge discharge when there is no thruster beam current. It also serves as a partial shield from ion impingement from the thruster beam. It is machined and formed from 0.08-centimeter-thick tantalum sheet (AMS 7849 annealed) with a 0.64-centimeter-diameter hole in line with the cathode tip.

## Thruster and Gimbal Support

This support serves as the main structural member of the thruster system (see figs. 4, 5, 7, and 20). It is also an interface between the feed tanks, thruster chamber assembly, gimbal ring, and ground screen mounting. The support contains two gimbal bearing supports; pin puller pin support; the mounting surface for the plasma beam probe; two gimbal attachments; and structural support for the electrical terminals, connector, and feedthroughs for the electrical wiring. The structure is a single machined part (6061 T-6 aluminum) in the shape of a bowl with openings for clearance and mountings. The surfaces are iridited per MIL-C-5541A, type 1, grade C, class 3. This surface treatment was chosen in lieu of anodize to allow good electrical conduction. Ground straps were attached from the thruster-gimbal support to the gimbal ring and gimbal mounts located on the spacecraft.

## Feed Tanks

General description. - The feed tanks provided reservoirs (9-month supply) for liquid mercury that supplied the main cathode and neutralizer cathode assemblies (see fig. 20). Two separate tanks were required since it was desired to use the neutralizer system in a thruster experiment which required a different potential. In this experiment the neutralizer was voltage biased from 0 to 50 volts above ground. The main cathode tank operated at a positive voltage potential of 3000 volts. The two tanks operate in an identical manner. Liquid mercury is separated from nitrogen gas by a rubber diaphragm. The initial pressure is 24.13 newtons per square centimeter (35 psia) with a full tank and reduces to 10.34 newtons per square centimeter (15 psia) with an empty tank. The rubber diaphragm was used to separate the nitrogen gas and mercury and was supported by a perforated stainless-steel liner. The rubber diaphragm also served as a seal between the two tank halves.

Both tanks have identical fill valves. One valve is used for filling with mercury and the other is used for adding nitrogen gas. The fill valves are welded to the enclosure (see figs. 21 and 22). The valves function similar to that of an automobile valve. When the center plunger is depressed the valve is open. In the normal position the O-ring sealed the unit. The center plunger was held by a nut and washer to positively seal the valve during vibrational testing. A different cover from that shown in figure 22 is used for the filling operation. It has a tube extending from the top. The fill cap was designed so that the center plunger O-ring would seat and seal the system before the cap O-ring would unseat.

Main feed tank. - The main feed tank (13.5-kg capacity) is located on the centerline of the thruster and isolated from the lower position of thruster-gimbal support by six alumina oxide (96 percent  $\text{Al}_2\text{O}_3$ ) mounts. The tank flanges are sandwiched between two isolator disks (see fig. 21). The tank is fabricated from 0.05-centimeter-thick stainless steel and welded (tungsten inert gas per MIL-W-8611A) in an assembly to form two separate flange sections (see fig. 23). The flanges serve as a mounting surface and for sealing over the rubber diaphragm beads and clamping the liner.

In order to keep the thruster system compact the nitrogen gas reservoir was formed from a combination of geometric shapes, starting with a large spherical sector (16.5 cm radius) and ending with a conical section to match the internal diameter (13.0 cm) of the mounting flange. The large spherical sector and junction were designed as a shell of uniform strength. The liner was formed in the shape of a hemisphere (6.35 cm radius of 0.05 cm thick) with nine holes (0.47 cm diameter) to permit pressurizing of mercury at partial capacity. The upper half of the mercury reservoir is formed in the shape of a hemisphere (6.35 cm radius by 0.05-cm thick) and welded to two flanges that provided mounting and sealing surfaces. The butyl diaphragm (isobutylene-isoprene) was molded in the shape of a hemisphere (6.35 cm radius by 0.15 cm thick) with twelve radial ribs

(0.15 cm high by 0.075 cm high) and a circular bead (14.05 cm diameter by 0.53 cm diameter cross section). The ribs were necessary to provide rigidity and avoid excessive sticking to the liner.

Neutralizer feed tank. - This tank (0.9-kg capacity) is offset from the main feed tank location and isolated from the thruster-gimbal support by three alumina oxide mountings. To allow adequate clearance and give a compact thruster the tank was supported on an auxiliary ring that is mounted to the upper portion of the thruster-gimbal support and by two pedestals that extended to the lower section of the thruster structure. The nitrogen gas reservoir is in the shape of a cylinder (4.85 cm diameter by 5.64 cm long by 0.05 cm thick) fabricated from 304 stainless steel and tungsten inert gas welded to a machined flange (see fig. 24). The liner (304 stainless steel (0.05 cm thick)) is formed in the shape of a hemisphere (2.42 cm radius) with four holes (0.48 cm diameter) to allow pressure at partial capacity. The mercury half is machined from 304 stainless steel in the shape of a hemisphere (4.34 cm radius by 0.15 cm wall thickness). The butyl rubber diaphragm (2.31 cm spherical radius by 0.076 cm thick) is formed in the shape of a combined hemisphere and extended cylinder to fit the liner and flange areas.

## Ground Screens

The entire thruster system was protected by ground screens (see figs. 21 and 25) to prevent backstreaming. It also provided support for layers of heat shielding that prevent the mercury in the neutralizer tube from freezing when the thruster is not operating and in a cold environment. The screens were formed in three sections so that the thruster, feed tanks, and the electric wiring could be assembled and inspected before final assembly of screens. The thruster-gimbal support served as an interface for mounting the ground screens. The screens were formed from perforated 304 stainless-steel sheet (0.048 cm thick) with 0.196-centimeter-diameter holes (46 percent open) spaced on 0.254-centimeter centers. Five raised circular beads were formed in the thruster screen (0.15 cm radius by 0.15 cm high) to give added structural support to the screen.

## Electrical Wiring

The electrical requirements were considered very carefully throughout the design and integration of the thruster system hardware in an effort to avoid high voltage breakdowns. The magnitudes and variations of the electrical requirements are summarized in table III and illustrated by a simple block diagram shown in figure 26. The perform-

ance and explanation of these requirements are described in references 2 and 3. The isolation and mounting techniques were partially covered in the description of the mechanical assemblies.

Electrical harness. - The prefabricated thruster electrical harness consisted of 13 lead wires (kapton coated) brought into the cover screen through a 304 stainless-steel feedthrough (see fig. 25). This cylindrical feedthrough (1.27 cm inside diameter by 1.90 cm long) provided a smooth rigid entrance. Inside the cover screen the separate lead wires were connected directly to the terminals without the use of a connector. An attempt was made to keep the leads with high potential together. The negative accelerator lead was located away from the positive high potential (see figs. 27 and 28).

Terminals and thruster lead wires. - The terminals were mounted around the main feed tank and next to the neutralizer feed tank (see fig. 27). Seven terminals were mounted on each of two 304 stainless-steel plates. These plates were screwed to the thruster-gimbal support. The terminals consisted of straight wall insulator terminals (Ceramaseals 801B0666-6, 96 percent  $\text{Al}_2\text{O}_3$ ) with a brazable or weldable mount (see fig. 29). The terminal mounts were spot welded to the stainless-steel plates. Inside the thruster bare solid copper leads were used in most cases. The thruster cathode keeper lead was a coaxial configuration from thruster terminal to keeper. The leads to the hermetic seal junction for heater power were made by using a small section of copper tubing (see fig. 21). The tubing was crimped over the leads and silver soldered. The negative high voltage accelerator lead was connected to a terminal which was brazed to a mounted bracket of the distributor enclosure. The lead was continued from this terminal directly to the accelerator (see fig. 30). A shadow shield was brazed to the lead to prevent the mercury from coating the ceramic portion.

Sensor wiring. - One pressure sensor and three temperature sensors were located on the thruster system. Since the voltages for the sensors were low, a commercial connector was used (see fig. 27). A voltage limiter box was installed for protection against possible high voltages from the pressure sensor on the neutralizer feed tank. Two lead wires were routed to a potted isolated thermister on the flange of the neutralizer feed tank. Four other leads to sun sensor thermisters were supported by cable ties and additional tabs that were spot welded to the thruster ground screens.

## THRUSTER TESTS

A large number of environmental tests were performed on the ground to validate the performance of the separate thruster systems and also integrated with the spacecraft. Some of the test results are covered in references 2 to 5. Only the vibrational and shock tests are covered in this report.

A series of vibration and shock tests were performed on the subsystems and the thruster system. The suspected critical areas in the experimental subassemblies passed the vibrational and shock specifications listed in table II. The thruster system was vibrated and shocked a total of 15 times in three axes mounted to the spacecraft as a fixture. The experimental system was mounted to an experimental spacecraft as a fixture. The mass of the second thruster and other components were simulated by weights. With the thruster system mounted on the spacecraft the dynamic specifications were reduced to approximately one-half of that listed in table II. In the initial thruster system test several deficiencies were discovered and corrected. After 3 minutes in the random vibration the welded tantalum tube joint to the main feed tank broke loose. Three electric leads were broken or loose and the screws holding the top ball mounts came loose. The feed tank tube had been weakened at the joint by a counterbore for accepting a (0.038 cm inside diameter) snubber. The feed tank junction fault was corrected by adding a tantalum sleeve (0.32 cm inside diameter by 0.05 cm thick wall by 0.48 cm long) over the tantalum tube and extending inside the tantalum mounting flange on the feed tank. The joint was electron beam welded on the flange side and tungsten inert gas brazed using copper as a filler on the tube side. The lead mountings and the tie downs were revised and the torque was increased on the screws. The vibrational and shock tests were repeated without any failures.

Due to developmental problems discovered in the feed system, the thruster system was vibrated and checked ten additional times. During the continual testing, the vaporizer joint to dummy isolator failed. This tantalum tube was replaced with a stainless-steel tube that was compatible with the material of the dummy isolator. After this correction the thruster system passed its final qualification test on the spacecraft fixture and the flight vibrational and shock testing on the flight spacecraft without any failures.

## CONCLUDING REMARKS

The SERT II spacecraft was launched into a near polar orbit of 1000-kilometer altitudes on February 3, 1970, from Vandenberg Air Force Base into the Western Test Range by a Thorad-Agena launch vehicle. The standby thruster was operated first. It was started on February 10, 1970, and ran for 2 days to confirm operation in space before it was shut down. The primary thruster was started on February 14, 1970, and ran until July 23, 1970, when a high voltage short shut down the system. There were two brief interruptions of operation during that period. The system was shut down for about 17.5 hours during the solar eclipse of March 7, 1970, and on May 21, 1970 the thruster system shut itself down for about 10 hours because of excessive high voltage cycling. The standby thruster was restarted on July 24, 1970, and ran until October 17, 1970, when a high voltage short also shut down this system. One interruption of that running time

was made for an eclipse. The primary thruster accumulated 3782 hours of space operation, and the standby thruster accumulated 2011 hours. It is believed that the cause of failure was due to ion sputtering between the screen grid and accelerator plate in the vicinity of the neutralizer. The undercutting and wear on the molybdenum plates in zero gravity caused molybdenum particles to adhere and finally join thus causing the short.

The mechanical design of the thrusters was proven satisfactory by passing all of the ground environmental and structural dynamics tests and by being successfully launched and operated in space. The operation, storage for over 6 months in space, and the restarting of the standby thruster was a success. The length of time in space also proved that the choice of materials, arrangements, and fabrication techniques fulfilled the thruster's needs.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, November 18, 1971,  
113-31.

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2. Byers, David C.; and Staggs, John F.: SERT II Flight-Type Thruster System Performance. Paper 69-235, AIAA, Mar. 1969.
3. Bagwell, James W.; Hoffman, Anthony C.; Leser, Robert J.; Reader, Karl F.; Stover, John B.; and Vasicek, Richard W.: Review of SERT II Power Conditioning. NASA TM X-2085, 1971.
4. Kerslake, William R.; Byers, David C.; and Staggs, John F.: SERT II Experimental Thruster System. Paper 67-700, AIAA, Sept. 1967.
5. Kerslake, W. R.; Byers, D. C.; Rawlin, V. K.; Jones, S. G.; and Berkopec, F. D.: Flight and Ground Performance of the SERT II Thruster. Paper 70-1125, AIAA, Aug. 1970.

TABLE I. - THRUSTER SPECIFICATIONS

Thrust, g . . . . .	2.81
Effective specific impulse, sec . . . . .	4 450
Beam current, A . . . . .	0.25
Beam voltage, V . . . . .	3 000
Nominal power, W . . . . .	1 000
Overall power efficiency, percent . . . . .	86
Overall propellant efficiency (including neutralizer), percent . . . . .	81
Thruster efficiency, percent . . . . .	70
Mission lifetime, months . . . . .	6
Design lifetime, hr . . . . .	10 000
Thruster system mass (less propellant), kg . . . . .	9
Main propellant mass (9-month supply), kg . . . . .	14
Thruster and neutralizer mass (less propellant tanks), kg . . . . .	3

TABLE II. - DYNAMIC ENVIRONMENTAL  
SPECIFICATIONS

Sinusoidal vibration		
Frequency range, Hz	Acceleration range	
5 to 19	1.27 cm double amplitude	
19 to 2000	9.0 g's (zero to peak)	
Random vibration		
Frequency range, Hz	Acceleration level, g's rms	Spectral density, g <sup>2</sup> /Hz
20 to 400	6.5	0.11
400 to 2000	18.9	.22
Shock, ±30 g's for 8 msec duration		

TABLE III. - THRUSTER ELECTRICAL OUTPUT REQUIREMENTS

	Rated output <sup>a</sup>			Typical operating output <sup>a</sup>		
	Voltage, V	Current, A	Power, W	Voltage, V	Current, A	Power, W
Propellant feed vaporizer, V2	3.6 ac	3.0	10.8	1.78 ac	1.7	3.0
Cathode, V3	17 ac	3.4	57.8	5.2 ac	1.5	7.8
Anode, V4	45 dc	2.6	117	37.4 dc	1.7	63
Screen, V5	3000 dc	.26	780	3000 dc	.255	765
Accelerator, V6	-1800 dc	.05	90	-1550 dc	.0019	3.0
Neutralizer cathode and neutralizer vaporizer, V7	13 ac	3.4	44.2	5.8 ac	1.9	11.0
Neutralizer keeper, V8	30 dc	.23	7	23 dc	.183	4.2
Neutralizer bias, V9	50 dc	.25	13	0	0	0
Cathode keeper, V10	20 dc	.35	7	11.7 dc	.30	3.5
Total power			1126.8			860.5

<sup>a</sup>For nominal input voltage of 60 V dc.

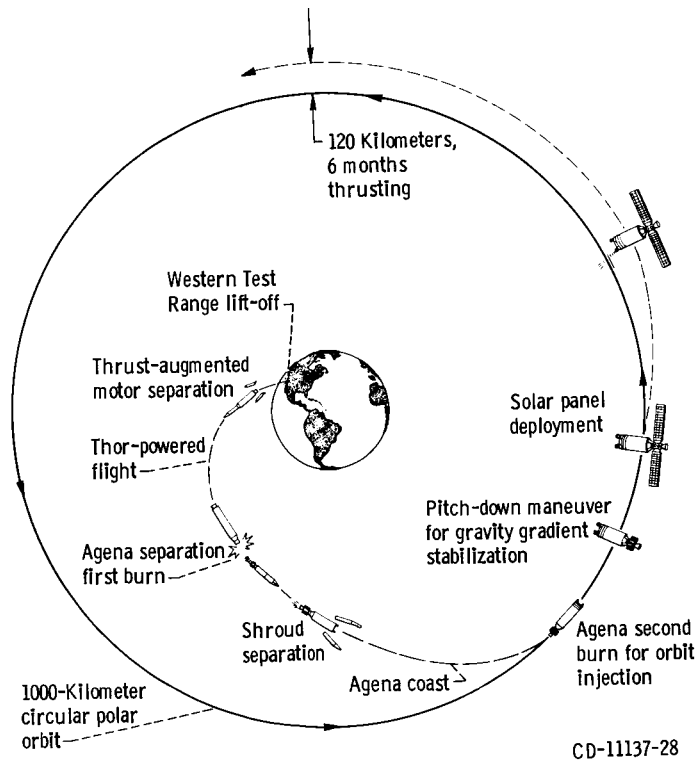


Figure 1. - Representation of SERT II flight sequence.

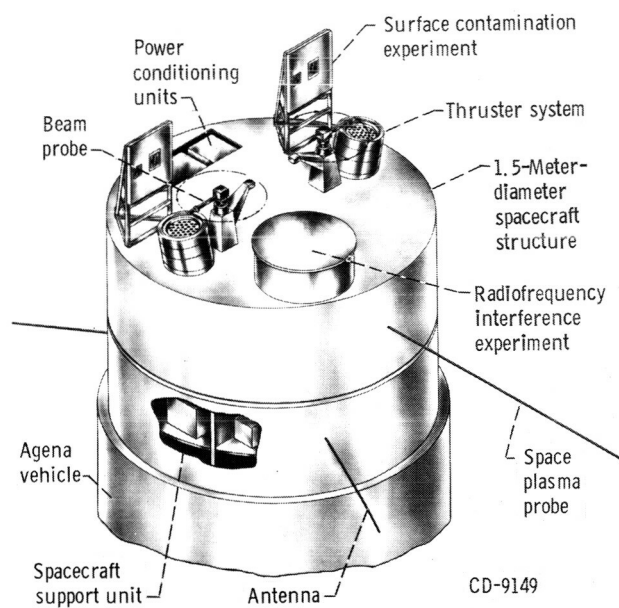


Figure 2. - SERT II spacecraft and support unit.

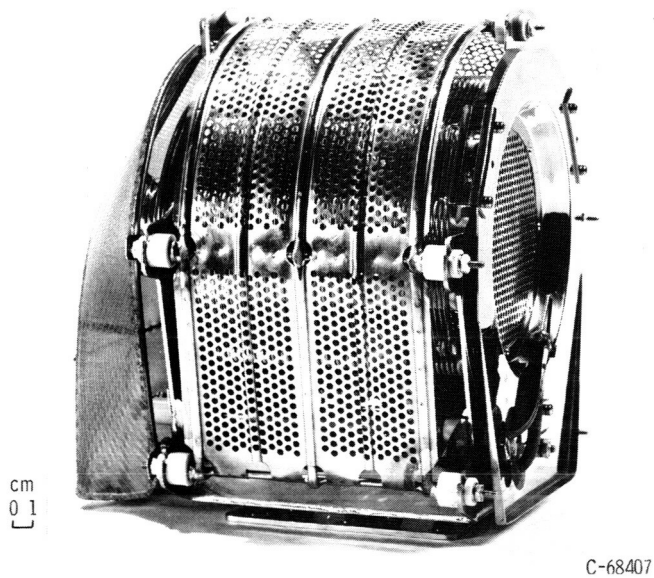
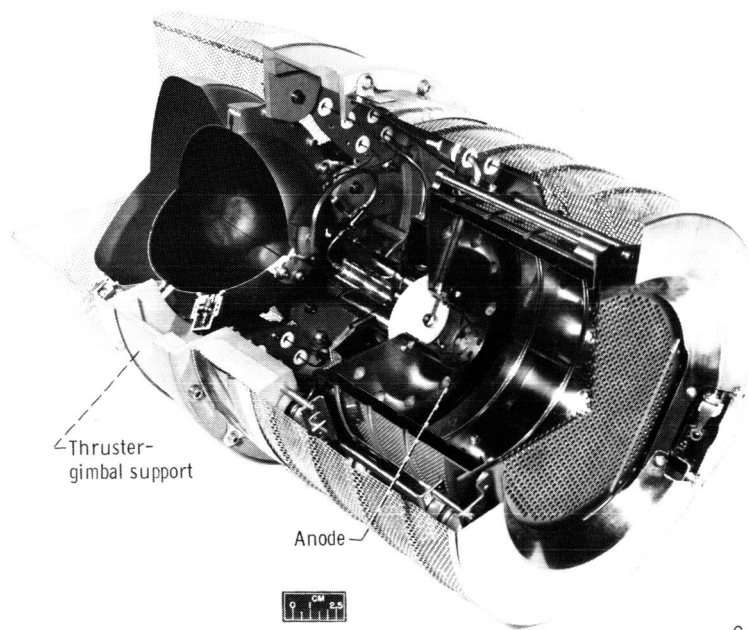
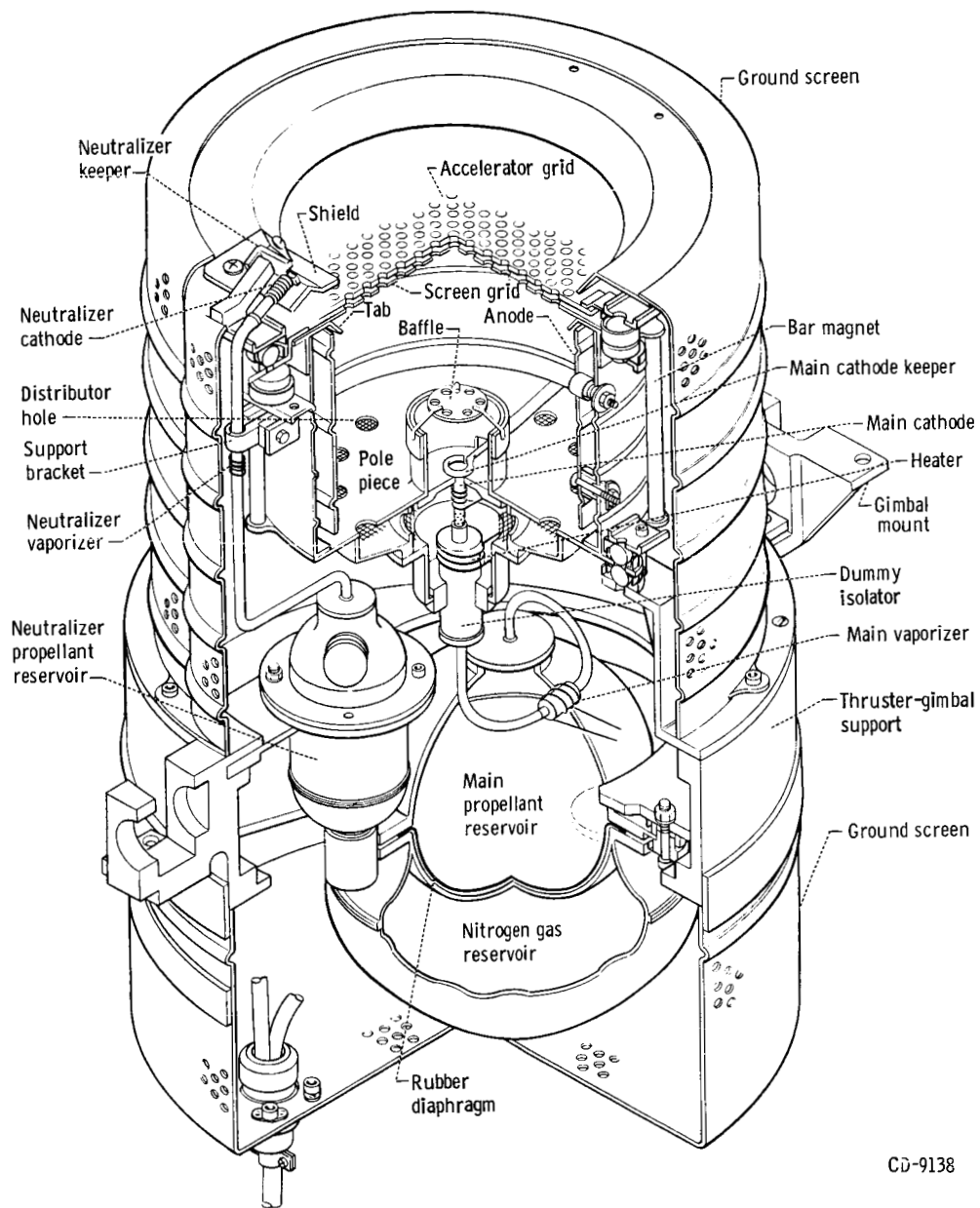


Figure 3. - SERT I thruster.



C-71-367

Figure 4. - SERT II thruster system.



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Figure 5. - Quarter section view of SERT II thruster system.

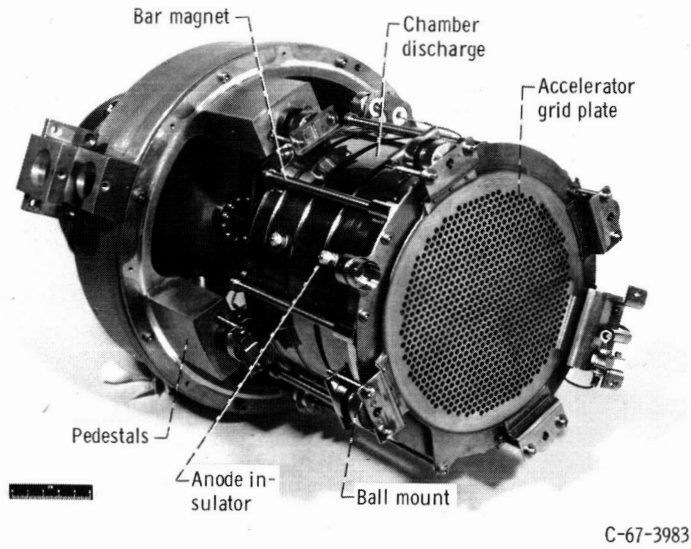


Figure 6. - Thrust chamber.

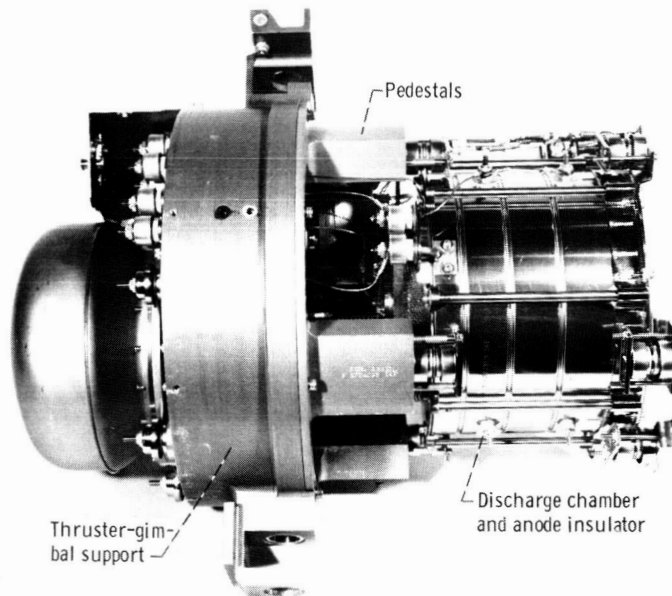


Figure 7. - Thrust chamber and mounting.

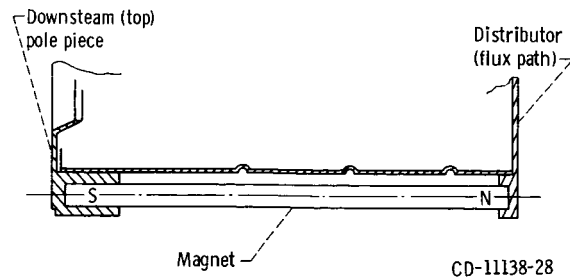


Figure 8. - Magnet and pole piece mount.

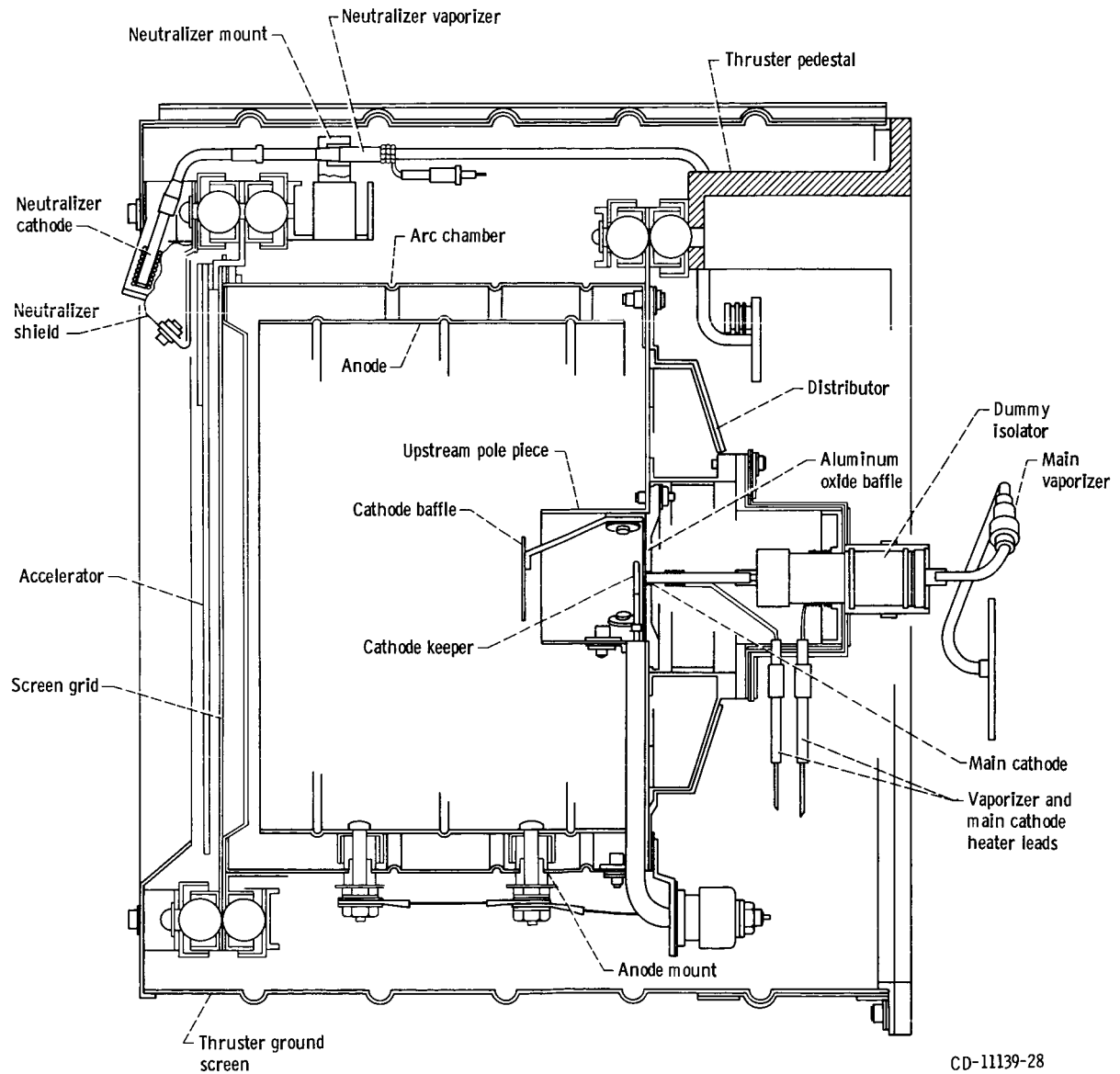


Figure 9. - Thruster section.

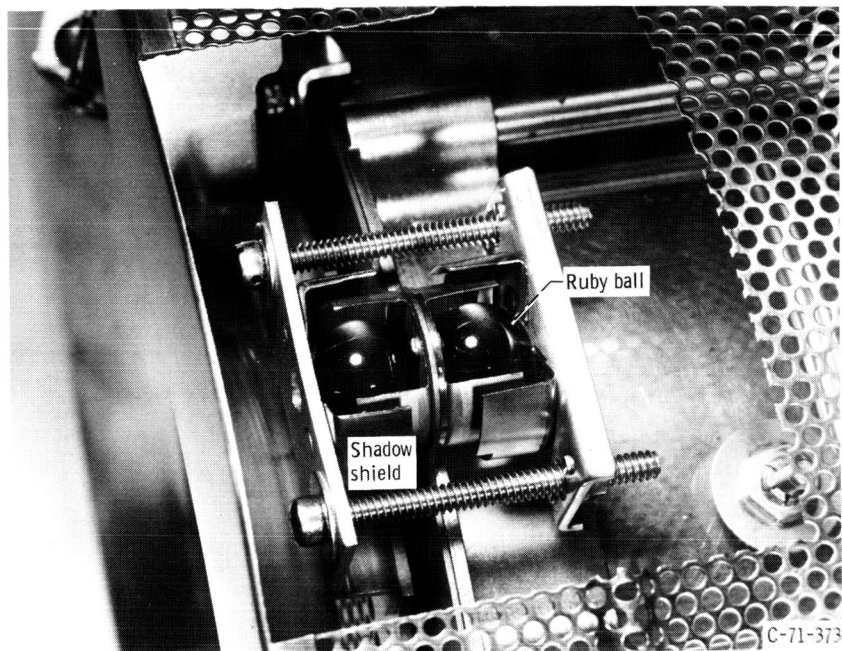
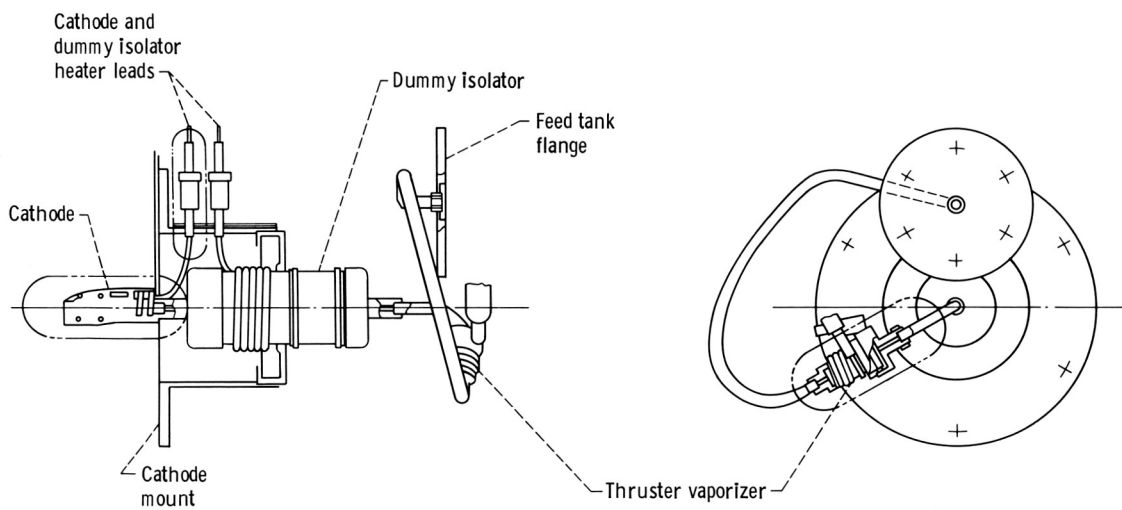


Figure 10. - Accelerator to screen grid isolation mount.



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Figure 11. - Cathode, cathode mount, dummy isolator, vaporizer, and tank flange.

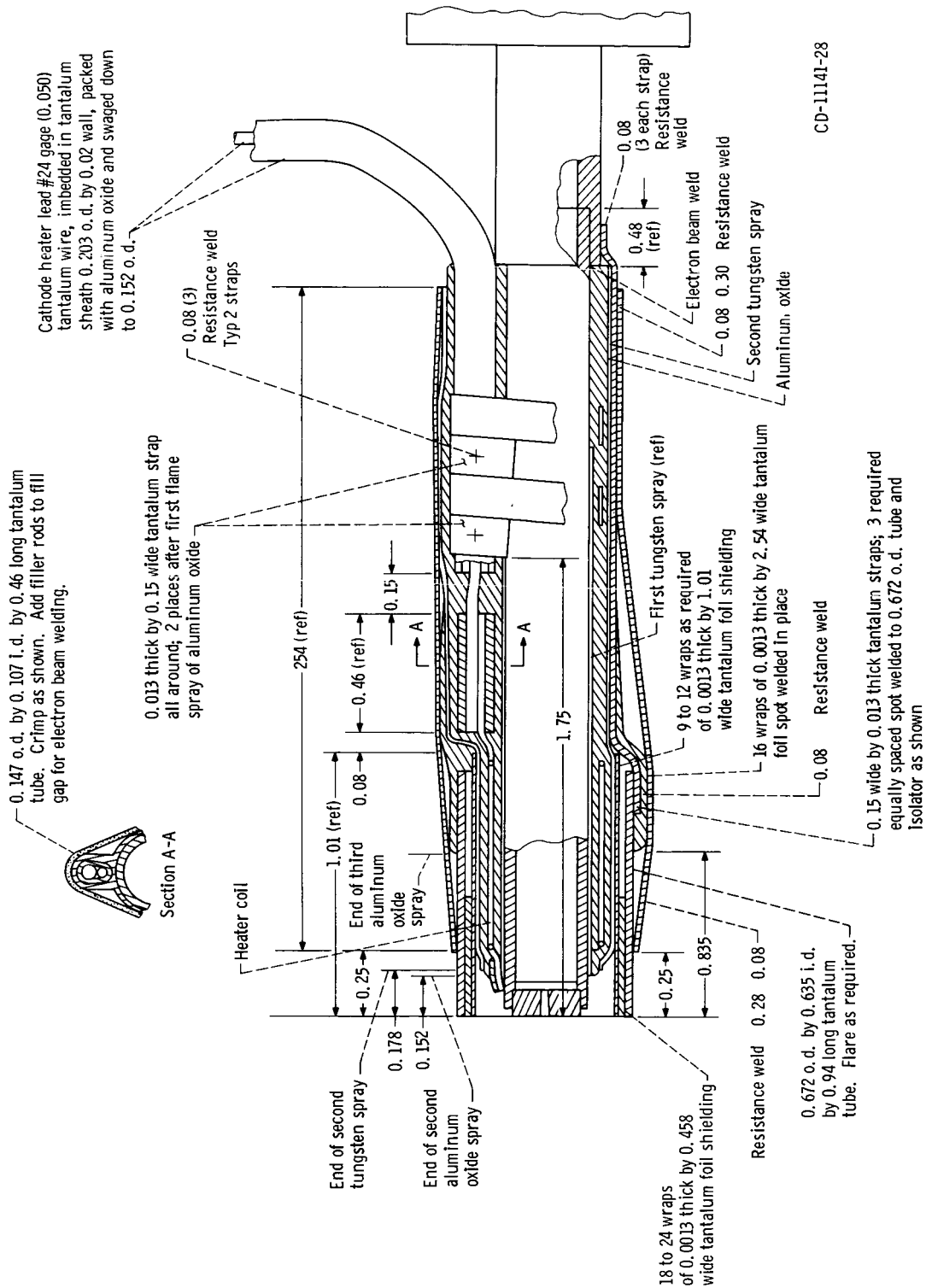


Figure 12. - Thruster cathode. (All dimensions in cm.)

Figure 13. - Thruster vaporizer. (All dimensions in cm.)

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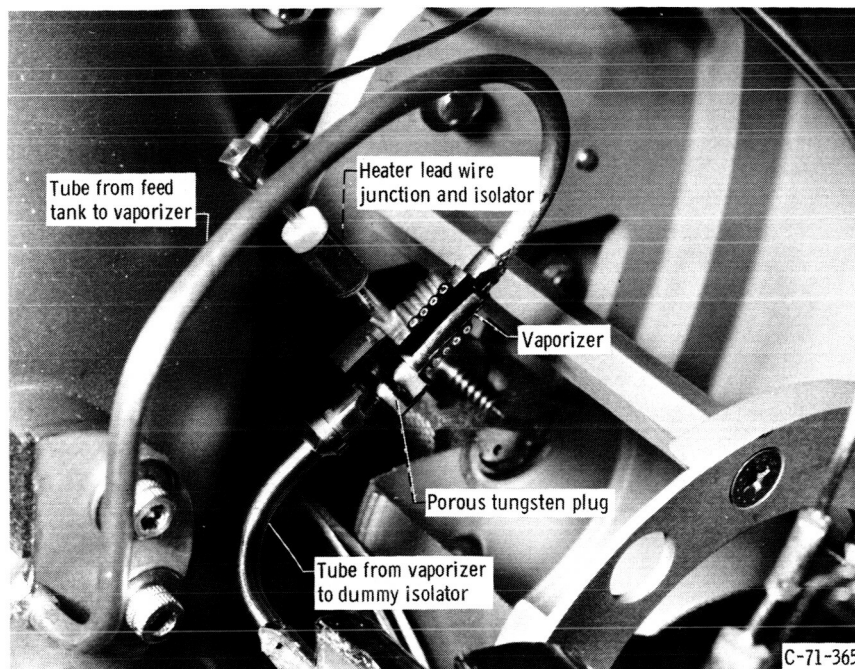


Figure 14. - Quarter section of thruster vaporizer.

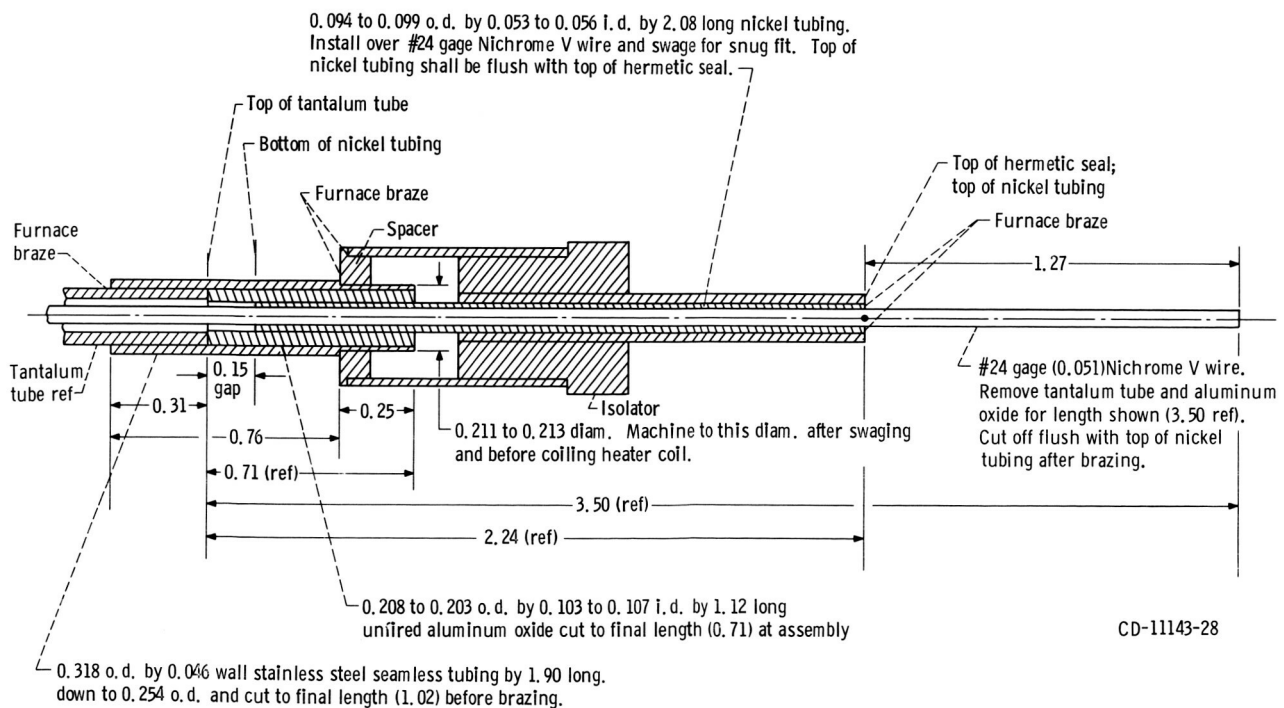


Figure 15. - Heater lead to hermetic seal junction assembly. (All dimensions in cm.)

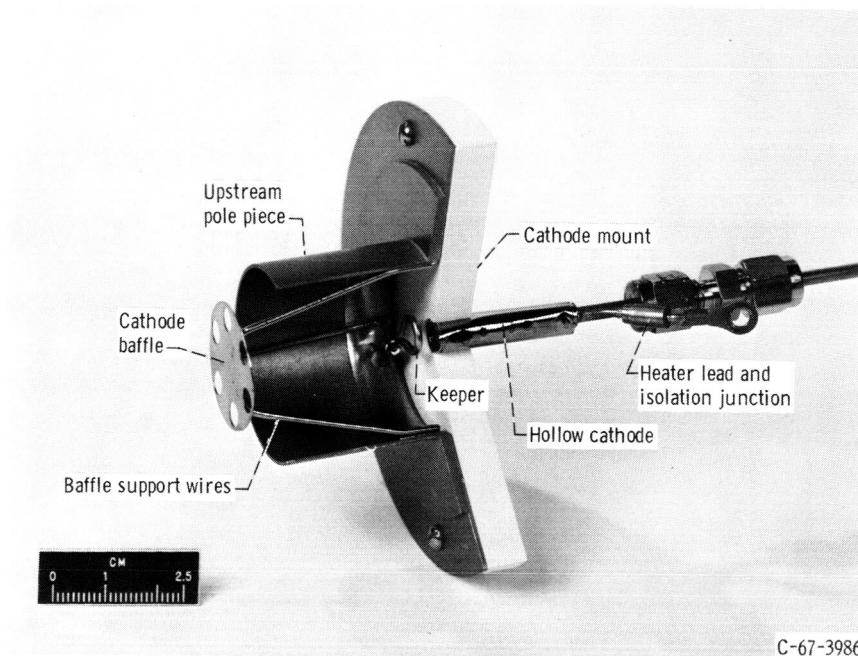


Figure 16. - Main cathode subassembly mockup.

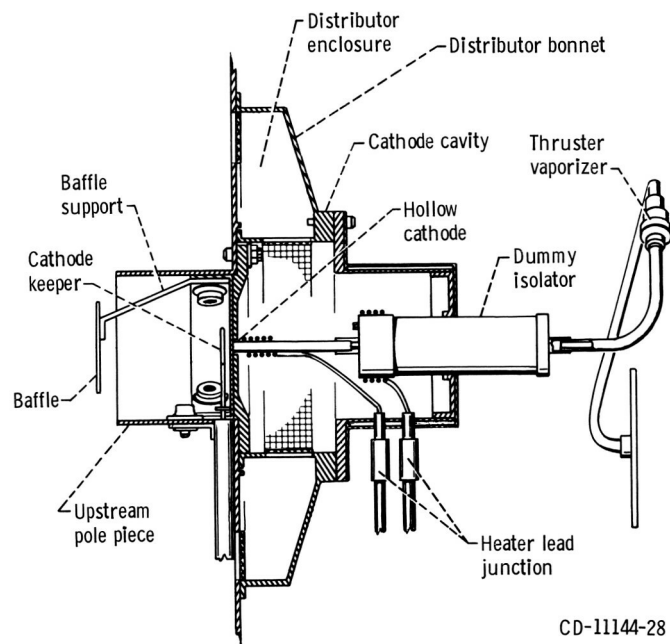


Figure 17. - Cross-sectional view of main cathode assembly.

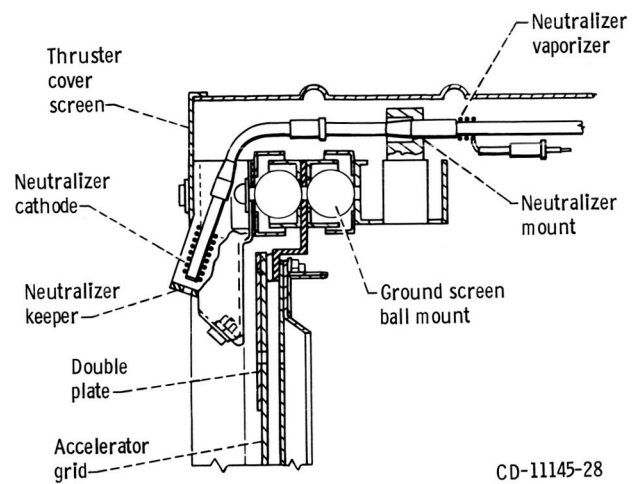


Figure 18. - Cross-sectional view of neutralizer assembly.

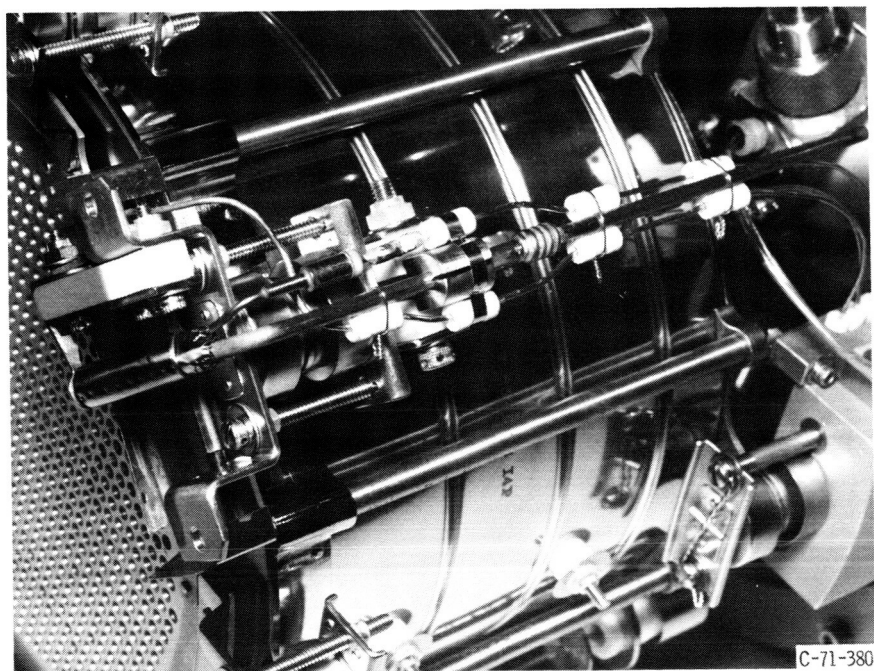


Figure 19. - Neutralizer assembly.

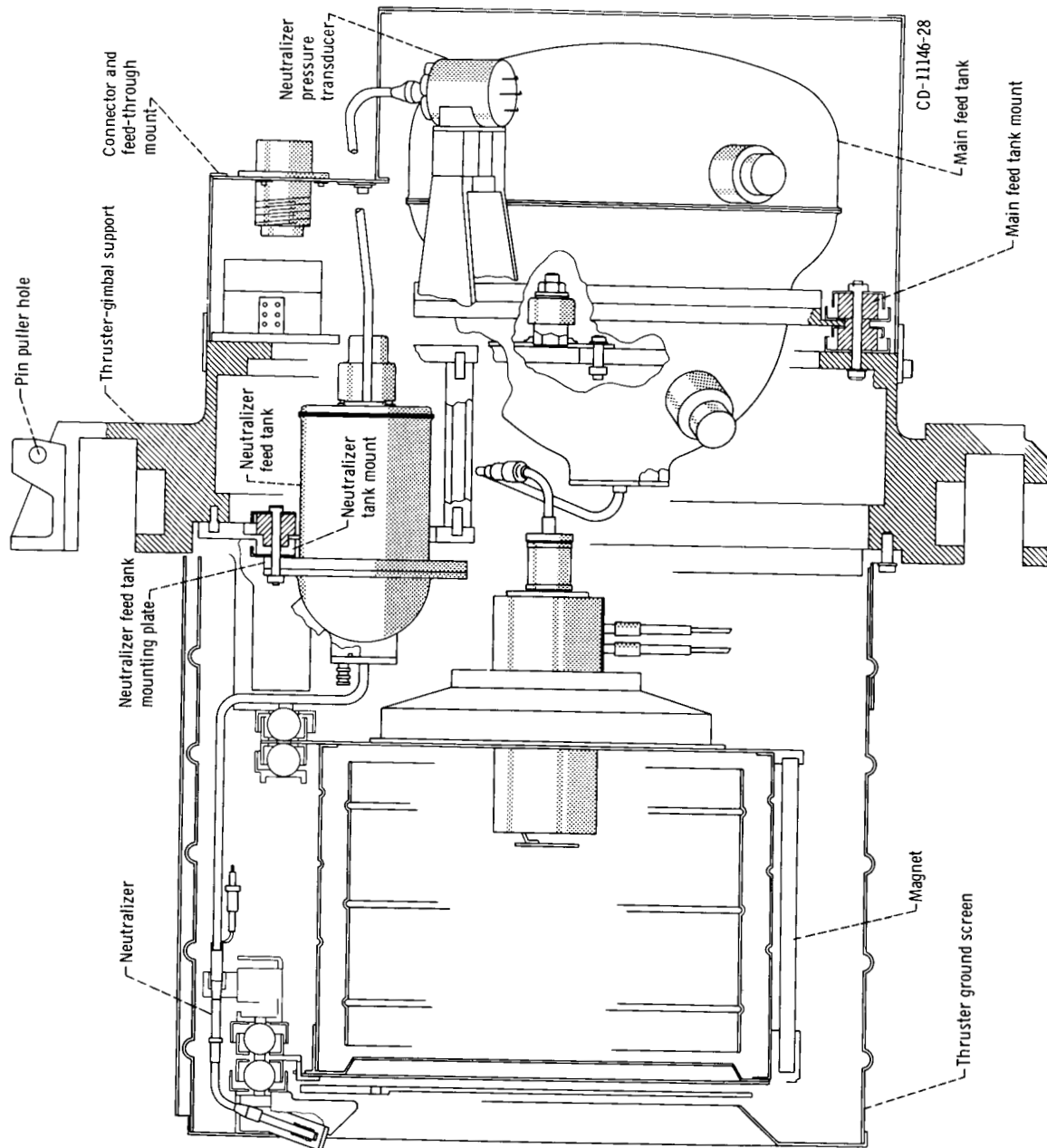
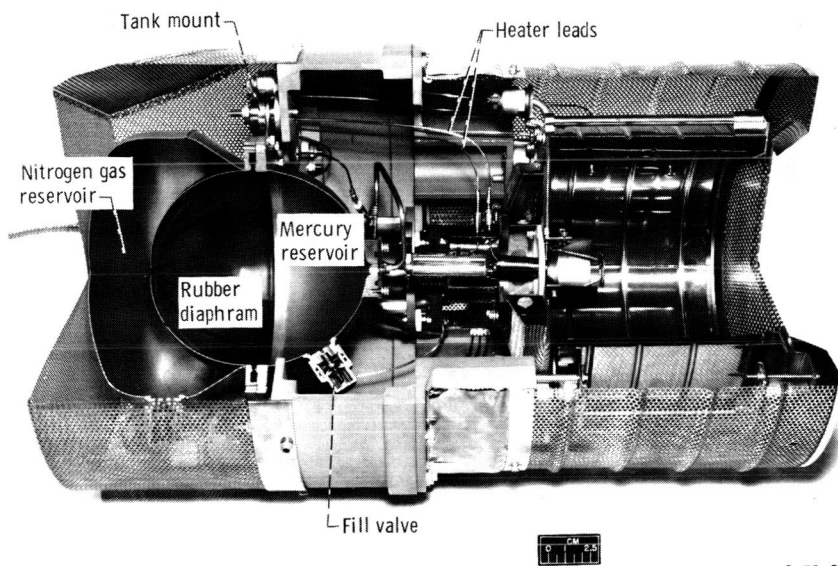
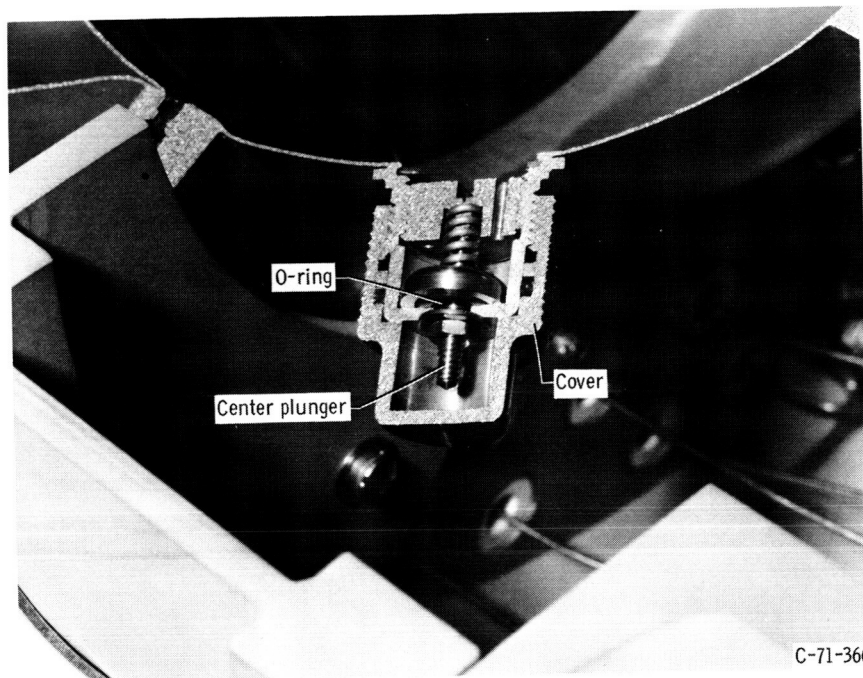


Figure 20. - Thruster system assembly.



C-71-368

Figure 21. - Thruster system assembly.



C-71-366

Figure 22. - Feed tank valve.

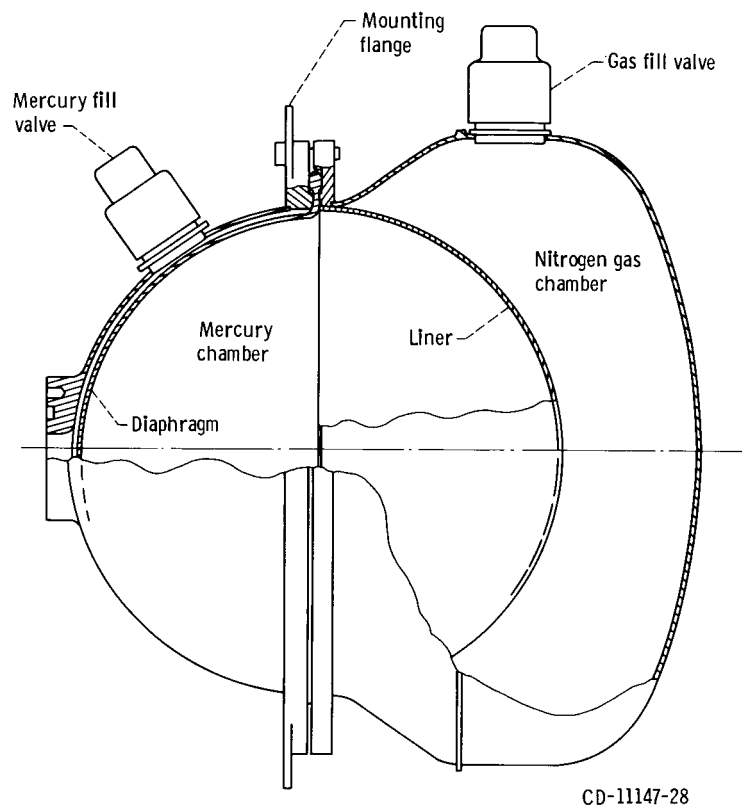


Figure 23. - Main feed tank.

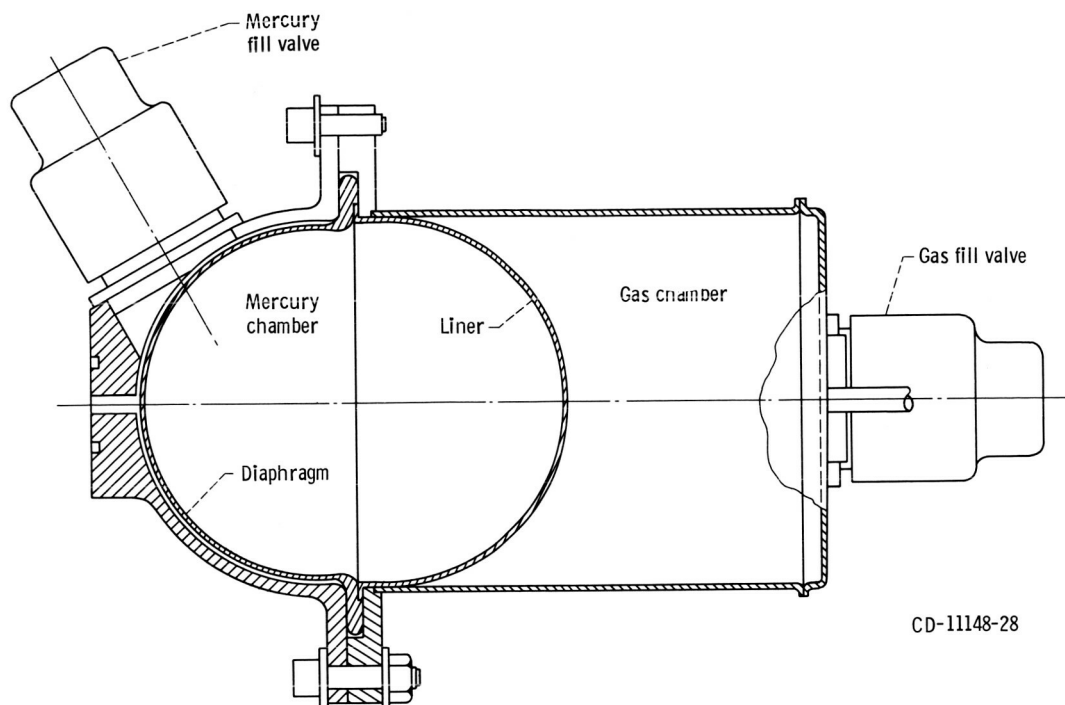


Figure 24. - Neutralizer feed tank.

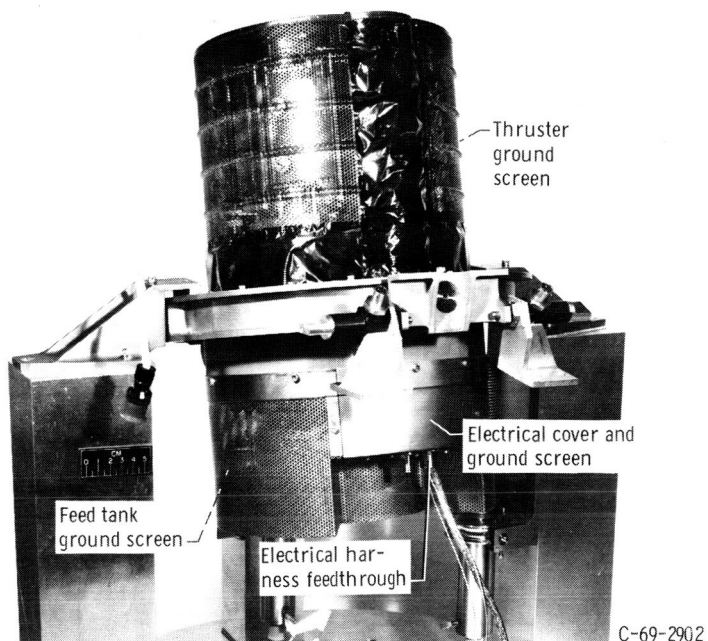


Figure 25. - Thruster ground screen.

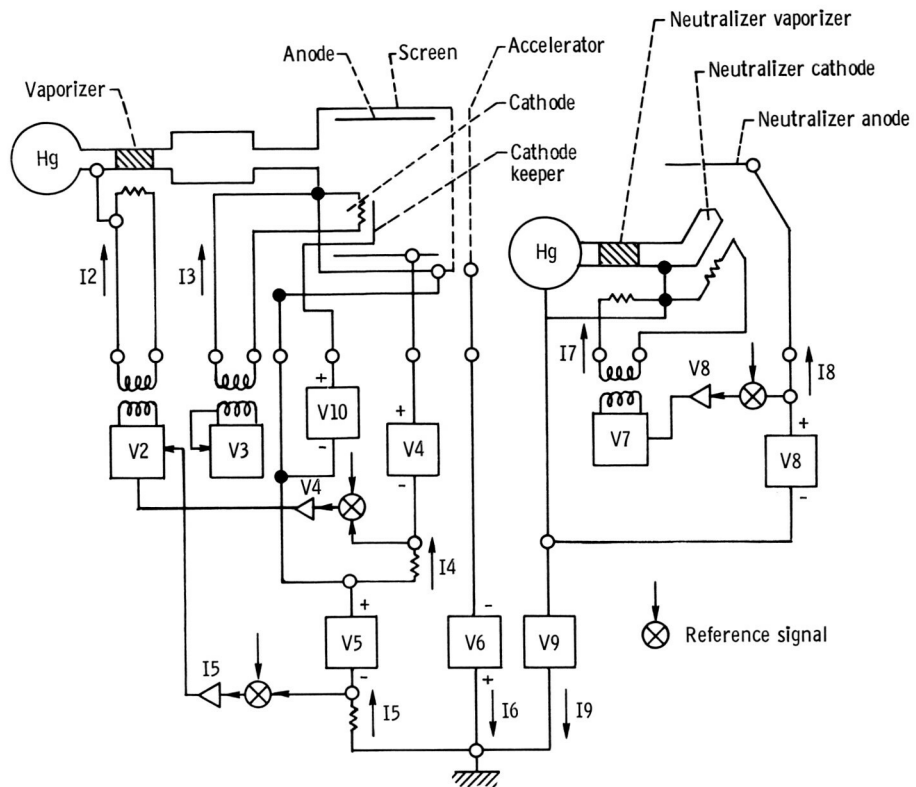


Figure 26. - Thruster electrical block diagram.

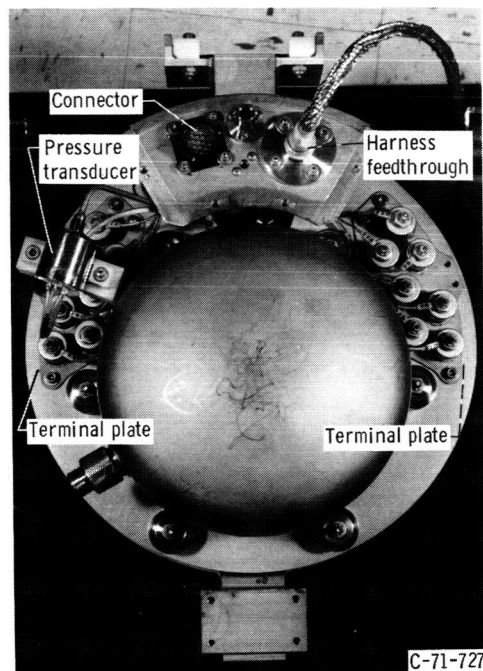
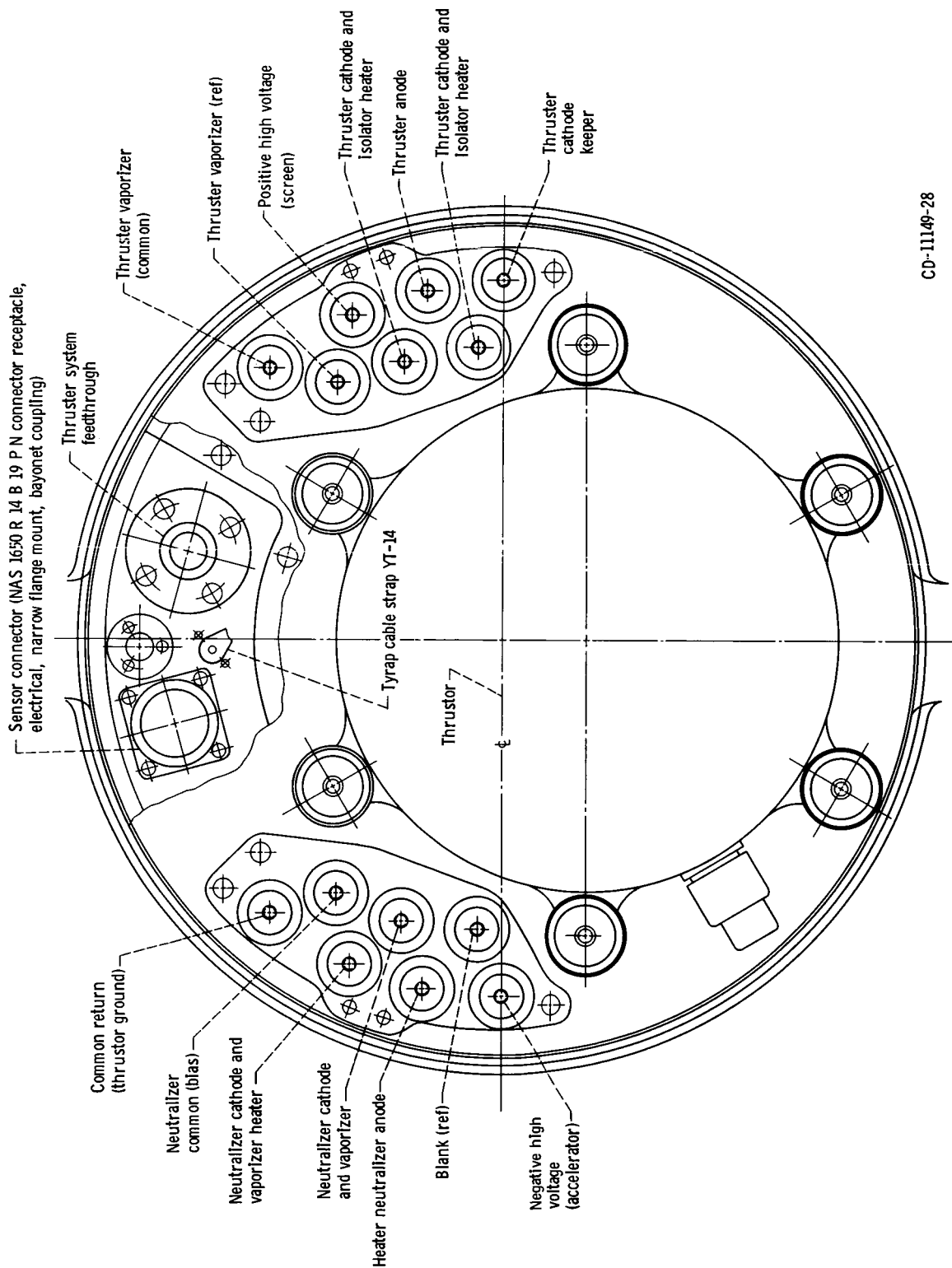
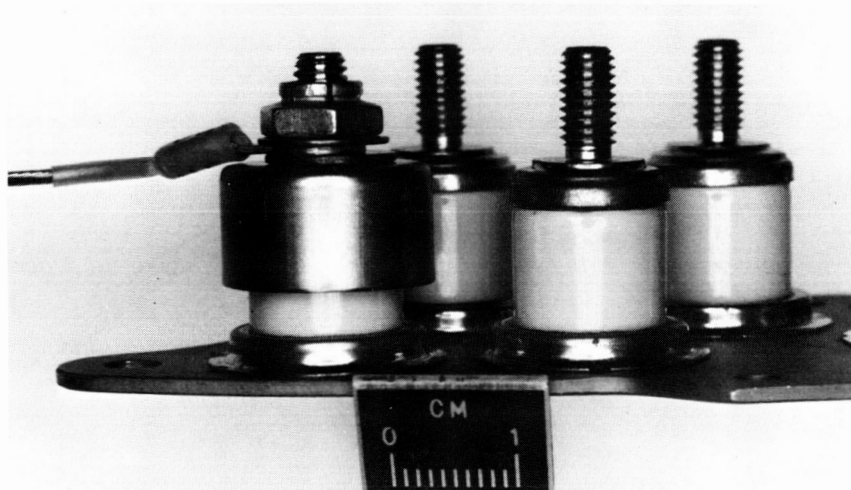


Figure 27. - Connectors, feedthroughs, and electrical harness.



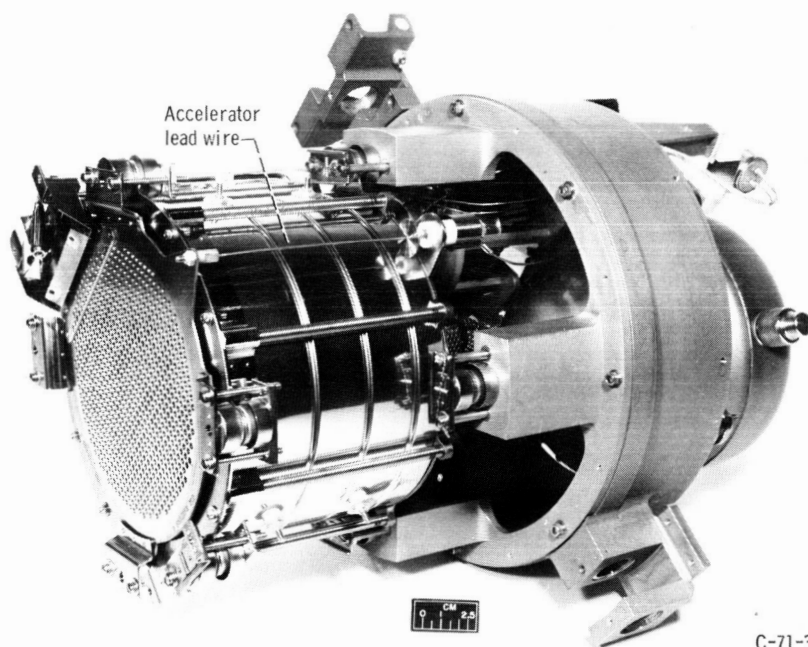
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Figure 28. - Electrical terminals.



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Figure 29. - High voltage terminals.



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Figure 30. - Thruster assembly.